

# Infrared frequency comb for frequency metrology based on a tunable repetition rate fiber laser

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## Abstract

A phase-locked, all-fiber supercontinuum source based on an ultrashort fiber ring laser with a tunable repetition rate is presented. The supercontinuum output is composed of a frequency comb with a spacing set by the laser repetition rate and an offset frequency determined by the carrier-envelope offset frequency. The laser repetition rate can be scanned over 400 kHz while the offset frequency remains phase-locked to a stable RF source.

## Introduction

A phase-locked, all-fiber supercontinuum source based on an ultrashort fiber laser has been developed for precision IR frequency metrology [1]. This source generates an octave-spanning supercontinuum [2] that is used to detect the carrier envelope offset (CEO) beat frequency [3-5]. The phase-locked supercontinuum exhibits narrow comb linewidths, which is an attractive feature for precision metrology of optical frequencies [6,7].

We have recently developed a second, all-fiber supercontinuum source based on an ultrashort fiber ring laser [8] with a tunable repetition rate. The compact design of the fiber laser allows us to easily change its repetition rate using a free-space delay line. The repetition rate can be scanned over a 400 kHz range while the laser remains mode-locked *and* the CEO beat frequency remains phase-locked to a stable RF source. The attractive features of the tunable repetition rate supercontinuum source are that it can be used to match the repetition rate of another pulsed source, it can be used for precision metrology without a wavelength meter [9], and it can be used to precisely scan the frequency of a cw laser locked to the comb. If a 1500 nm cw laser is locked to a tooth of the supercontinuum frequency comb, a change in repetition rate of 400 kHz would correspond to a 1.5 THz change in optical frequency of the cw laser.

## Experimental Measurements

Figure 1 depicts the supercontinuum source, which consists of an additive pulse mode-locked erbium fiber ring laser, an erbium-doped fiber amplifier (EDFA), and a length of UV exposed dispersion-flattened, highly nonlinear, dispersion-shifted fiber (HNLF) [10]. The additive-pulse mode-locked erbium fiber ring laser was operated in soliton mode, producing ultrashort pulses with 20 nm spectral bandwidth. A fiber-coupled free-space delay line in the fiber laser cavity allowed the repetition rate to be changed from 49.32 MHz to 50.14 MHz. The pulses from the laser were amplified and compressed to less than 100 fs in the EDFA before being injected into the UV exposed HNLF. The HNLF uses a combination of Ge and F dopants, in the unexposed fiber, to produce a nonlinear coefficient of  $\gamma \sim 10.6 \text{ W}^{-1} \text{ km}^{-1}$ , a dispersion of 1.74 ps/(nm km), and a dispersion slope of 0.009 ps/(nm<sup>2</sup> km) at 1550 nm. The exposure of the HNLF to UV radiation

increases the refractive index of the Ge-doped core, enhancing the short wavelength ( $<1100$  nm) portion of the supercontinuum. From a 30 cm length of UV exposed HNLF, the resulting supercontinuum spanned from 1000 nm to 2300 nm ( $\sim 140$  THz wide).

The CEO beat frequency was measured by mixing 1030 nm light with frequency-doubled 2060 nm light in an f-to-2f interferometer [3]. The 1030 nm and 2060 nm portions of the supercontinuum are shown in Fig. 2(a) along with the corresponding offset beat, Fig 2(b). The CEO beat frequency can be phase locked to a stable RF source. The repetition rate could also be phase locked to a stable RF source using a piezoelectric transducer (PZT) fiber stretcher in the laser cavity.

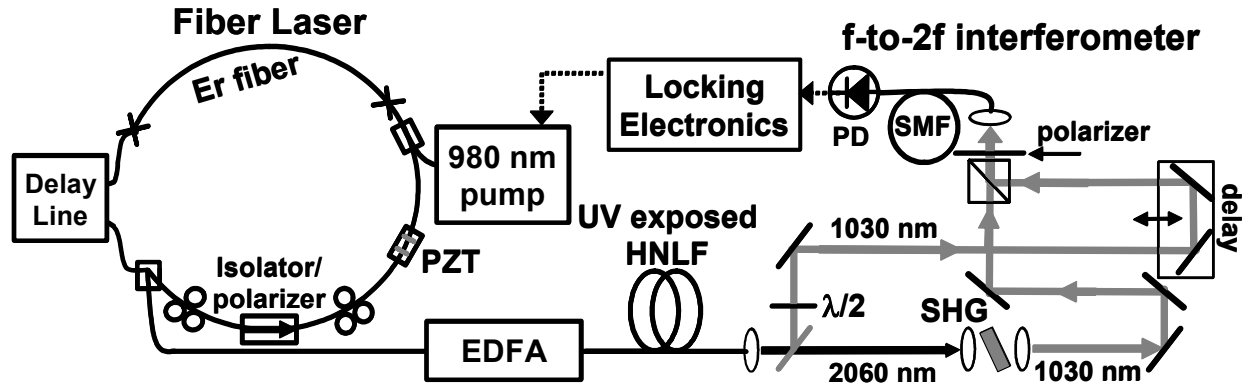


Fig 1. Schematic of the mode-locked fiber laser, erbium-doped fiber amplifier (EDFA), UV exposed highly nonlinear fiber (HNLF), and f-to-2f interferometer. The CEO beat frequency is detected by a photodetector (PD), and is used to control the 980 nm pump diode current. The thick solid lines represent free-space optical paths, the thin solid lines represent fiber optic paths and the dotted lines represent electrical paths.

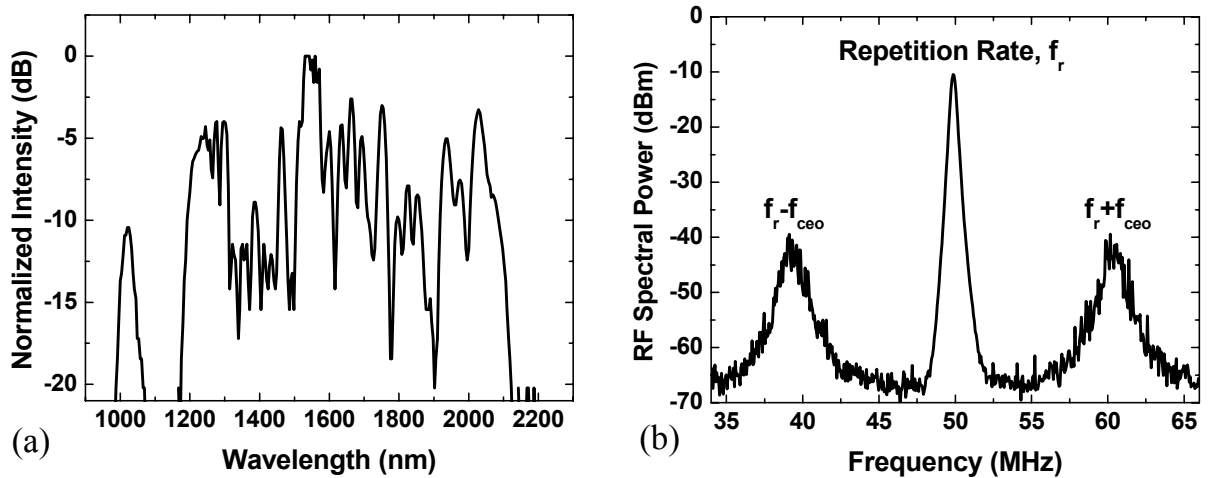


Fig 2. (a) The octave-spanning supercontinuum generated by the UV-exposed highly nonlinear fiber. (b) RF power spectrum from mixing the 1030 nm portion of the supercontinuum with the frequency-doubled 2060 nm portion. The repetition rate signal ( $f_r$ ) at 49.8 MHz and CEO beat frequency ( $f_{CEO}$ ) are clearly seen.

To demonstrate the utility of the variable repetition rate laser, the CEO beat frequency was locked and the repetition rate was scanned over a range by moving the in-cavity delay line.

The repetition rate was free-running for this experiment. To lock the CEO beat frequency, negative feedback to the 980 nm pump diode current was used. The RF signal from the f-to-2f interferometer was filtered at 120 MHz (this beat is at  $2f_r + f_{\text{CEO}}$ ), mixed up to 1120 MHz and divided in frequency by 256 (Fig. 3). The divided-down signal at 4.375 MHz was compared to a synthesizer, and the resulting phase error was used to control the 980 nm pump diode current. The divided-down and phase-locked CEO beat frequency had a standard deviation of  $\leq 25$  mHz.

Figure 4 shows the divided-down CEO beat frequency for repetition rate scans over 20 kHz and 400 kHz. The occasional cycle slips occurred due to non-optimization of the control electronics. Only one cycle slip was recorded over a 20 kHz range and four were recorded over the 400 kHz range. We are currently improving the CEO beat frequency lock to prevent phase slips from occurring over the full repetition rate scan of 0.82 MHz.

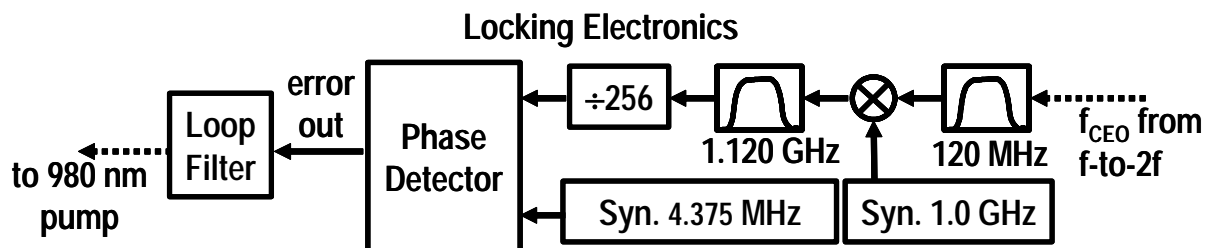


Fig. 3. The electronics used to phase-lock the CEO beat frequency. The  $f_{\text{CEO}}$  signal from the f-to-2f interferometer was filtered at 120 MHz, mixed with a 1 GHz signal, and divided by 256 in frequency. This signal is compared to a 4.375 MHz signal by a digital phase detector, and the error signal is used to control the 980 nm pump laser current. All synthesizers were referenced to a common time base.

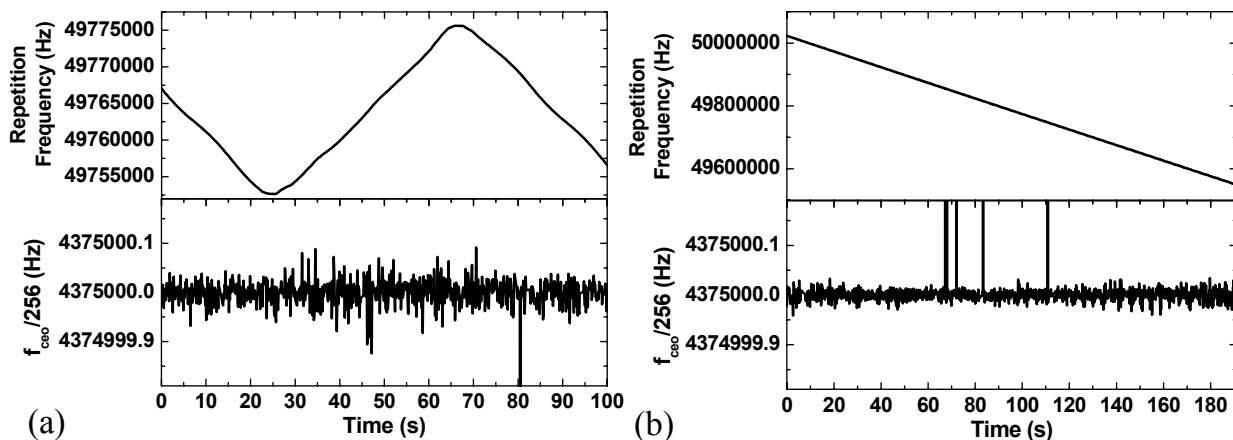


Fig. 4. Scanning the laser repetition rate while the CEO beat frequency ( $f_{\text{CEO}}$ ) is locked. (a) The divided-down CEO frequency experiences one phase slip as the repetition rate is scanned over a 20 kHz span in 100 s. (b) The divided-down CEO beat frequency remains locked over a 400 kHz span in 180 s.

A phase-locked frequency comb with a variable comb tooth separation has many potential uses for IR frequency metrology. For example, the ability to sweep the comb tooth separation allows one to distinguish the mode number of a single comb tooth without using a wavelength meter [9]. Also, a cw laser can be precisely scanned in frequency by locking it to a single comb tooth of the supercontinuum. With the CEO frequency phase-locked to the

synthesizer, a change in repetition rate of 400 kHz would correspond to a 1.5 THz change in the optical frequency of a comb tooth around 1500 nm. A cw laser locked to this comb tooth would then experience continuous tuning over 1.5 THz (12 nm). Finally, the tunable repetition rate will allow synchronization between two optical frequency combs for tests of comb stability [11].

## Conclusion

We have demonstrated the ability to phase-lock the CEO frequency of an all-fiber supercontinuum source while scanning its repetition rate, thus altering the comb spacing while the CEO frequency is fixed. A phase-locked near-IR frequency comb with a variable comb tooth separation has many potential benefits for near-IR frequency metrology.

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